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PROBLEMS OF FORCE MEASUREMENTS AND WEIGHING FOR THE DEVELOPMENT OF ROCKETS AND SPACE VEHICLES

by

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

* * *

45th ANNUAL TECHNICAL CONFERENCE
NATIONAL SCALE MEN'S ASSOCIATION
Liberty, New York
April 21, 1964

Gentlemen,

It is indeed a distinct pleasure to be speaking to you here at the occasion of your 45th Annual Conference. It is a special pleasure for me because it involves an area of technology, or better metrology, which is of particular interest to the National Aeronautics and Space Administration, and of which it also can be said, has been in use since the days of the ancient Egyptians who were also, as we are, interested in studies of the stars and planets.

Constant progress has been made since then, particularly in the last two to three decades, covering a wide range from the identification of minute trace quantities to the measurement of millions of pounds of thrust. Both of these pertain to measurement problems connected with NASA's effort in the exploration of space.

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To underline this wide range:

In Slide 1 we see the principle of a detector for meteoroids. By measuring the time it takes to pass through the two membranes, the velocity can be determined. A momentum balance which catches the particle yields velocity times mass. From both measurements, the mass itself can be calculated.

The next Slide 2 shows data from Explorer 16 Satellite which measured particle penetrations in 1 mil and 2 mil thick beryllium - copper sheaths. The slide shows the accumulated number of penetrations as they were reported by the satellite against days in orbit.

To identify the other extreme, in the next Slide 3, we see a scale-up of conventional and advanced concepts of rocket engine technology. The next Slide 4 gives a view of the M-1 engine. You can see the taxpayer is getting smaller and smaller all the time.

As I am to talk to you about weight and force measurement problems as applied to rockets and space vehicles, let me tell you briefly about our NASA programs and progress. As businessmen and industrialists, you are accustomed to measuring the performance of enterprises by the accomplished success. The nation's space program has moved in its five-year existence from the capability of putting modest satellites weighing but a few pounds in near-earth orbit to the Saturn I vehicle which has lifted over ten tons into the same orbit. So, I can report, that as of January, 1964, in the past 26 months, NASA has placed 26 satellites in earth orbit without a single launch vehicle failure. In the next Slide 5, I have combined these various missions, their identification and purpose. To give some examples: 4 Mercury astronaut flights, 5 Tiros weather satellites, Telstar, Relay and Syncom communications satellites, six Explorer scientific satellites, 2 International Scientific satellites, the Orbiting Solar Observatory, and the first successful launching of the Centaur rocket, which is a stepping stone for later advanced missions, because it proved the feasibility of using liquid hydrogen as fuel.

As a result, we have advanced our national knowledge of man's ability to exist in space; satellites and deep space probes have discovered the Van Allen radiation belts, the constant blowing solar wind, and have provided better knowledge of the conditions in the upper atmosphere: including discovery of the helium band, hydrogen layer and dust belts.

In order to achieve this success, many requirements had to be met, and many unique tests and measurements had to be performed with highest accuracy.

Although the greatest publicity has been given to the Manned Lunar Landing Program, the NASA effort is not confined to the single objective of landing men on the moon. Rather it is our aim to explore space along many scientific fronts. To achieve these multiple goals, a broad and sound foundation of research and advanced technology is needed to make coordinated and timely decisions as to future missions.

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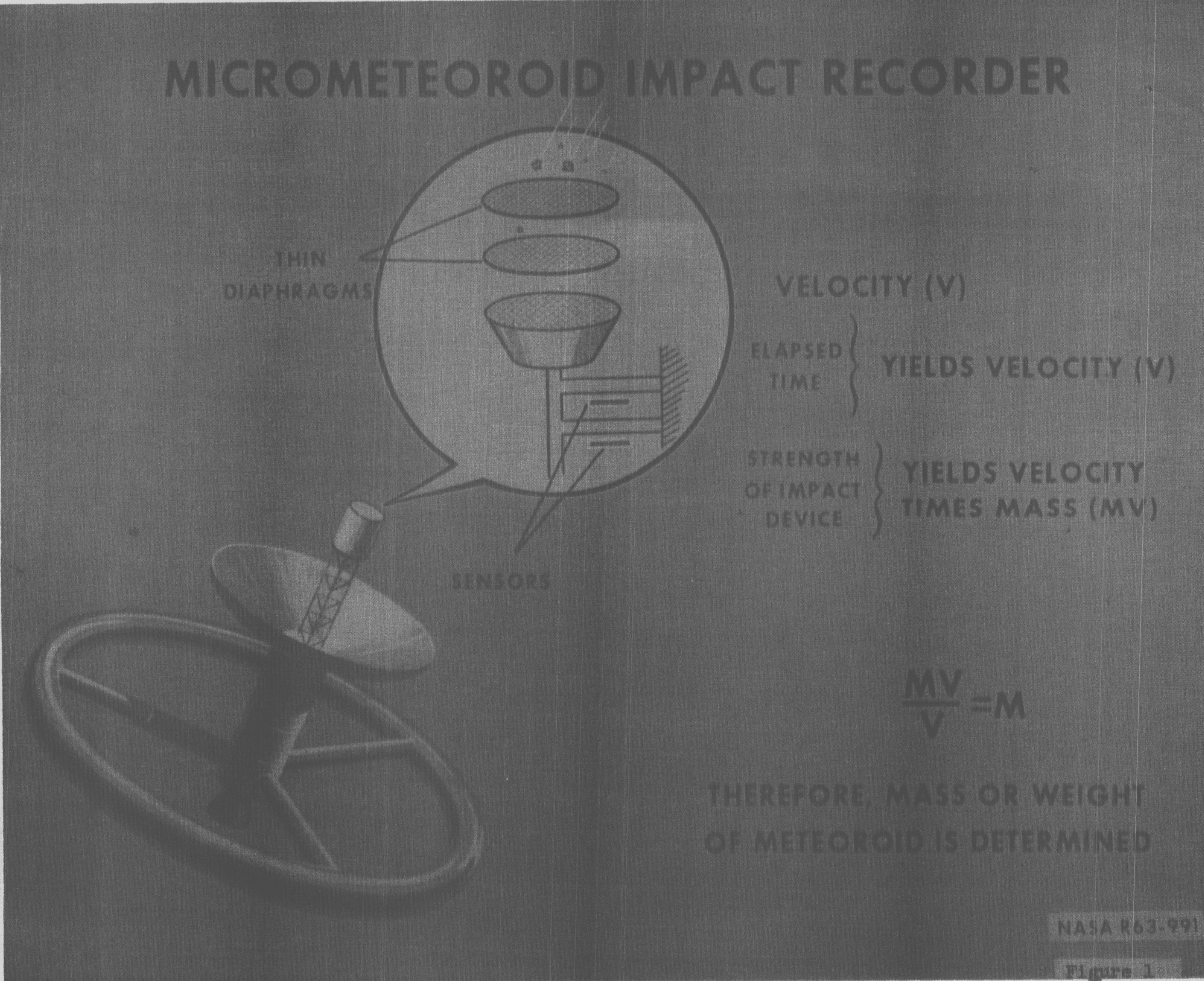
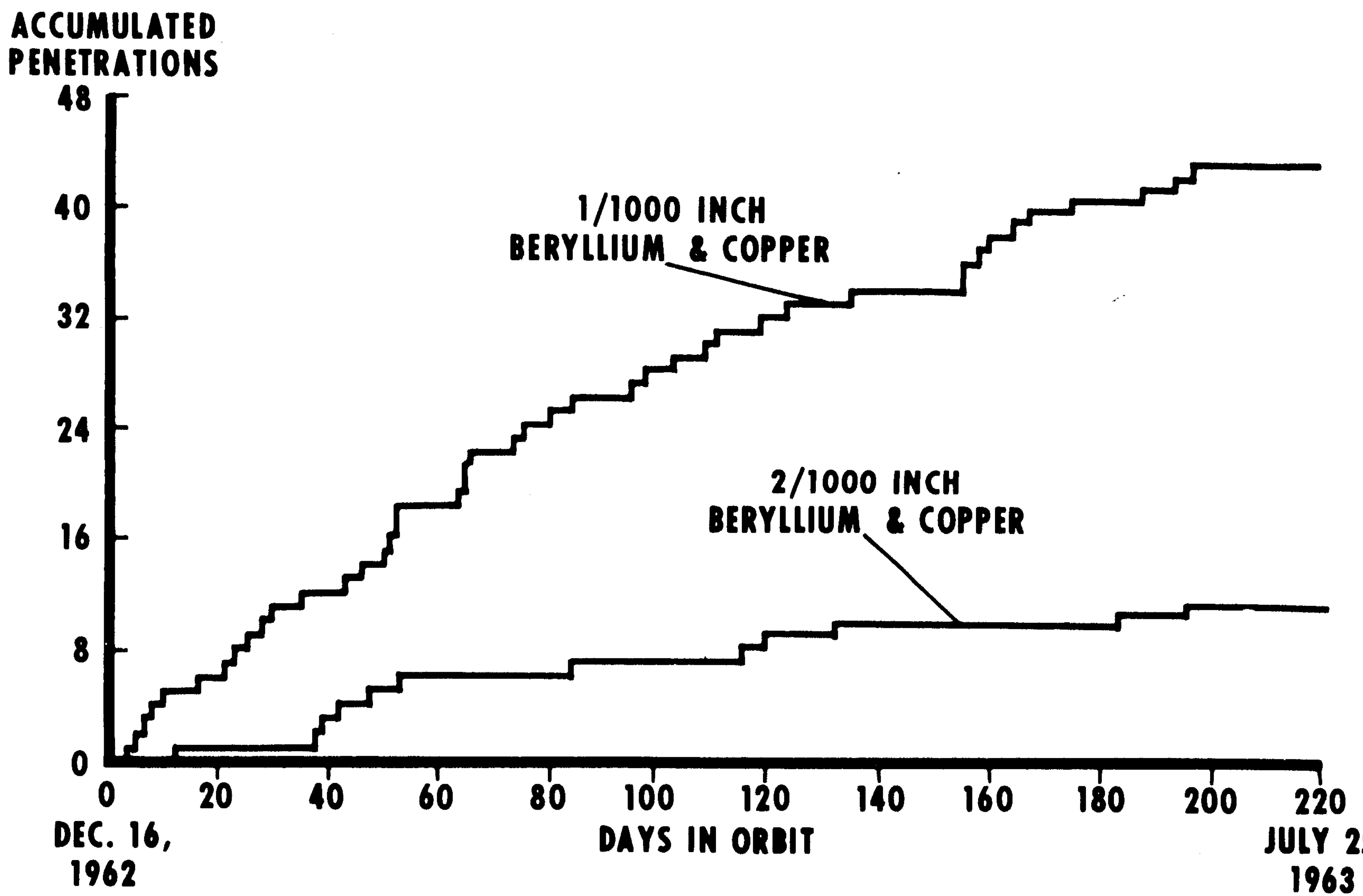

MICROMETEOROID IMPACT RECORDER
THIN DIAPHRAGMS
SENSORS
VELOCITY (V)
ELAPSED TIME
YIELDS VELOCITY (V)
STRENGTH OF IMPACT DEVICE
YIELDS VELOCITY TIMES MASS (MV)
$\frac{MV}{V} = M$
THEREFORE, MASS OR WEIGHT OF METEOROID IS DETERMINED
NASA R63-991

Figure 1

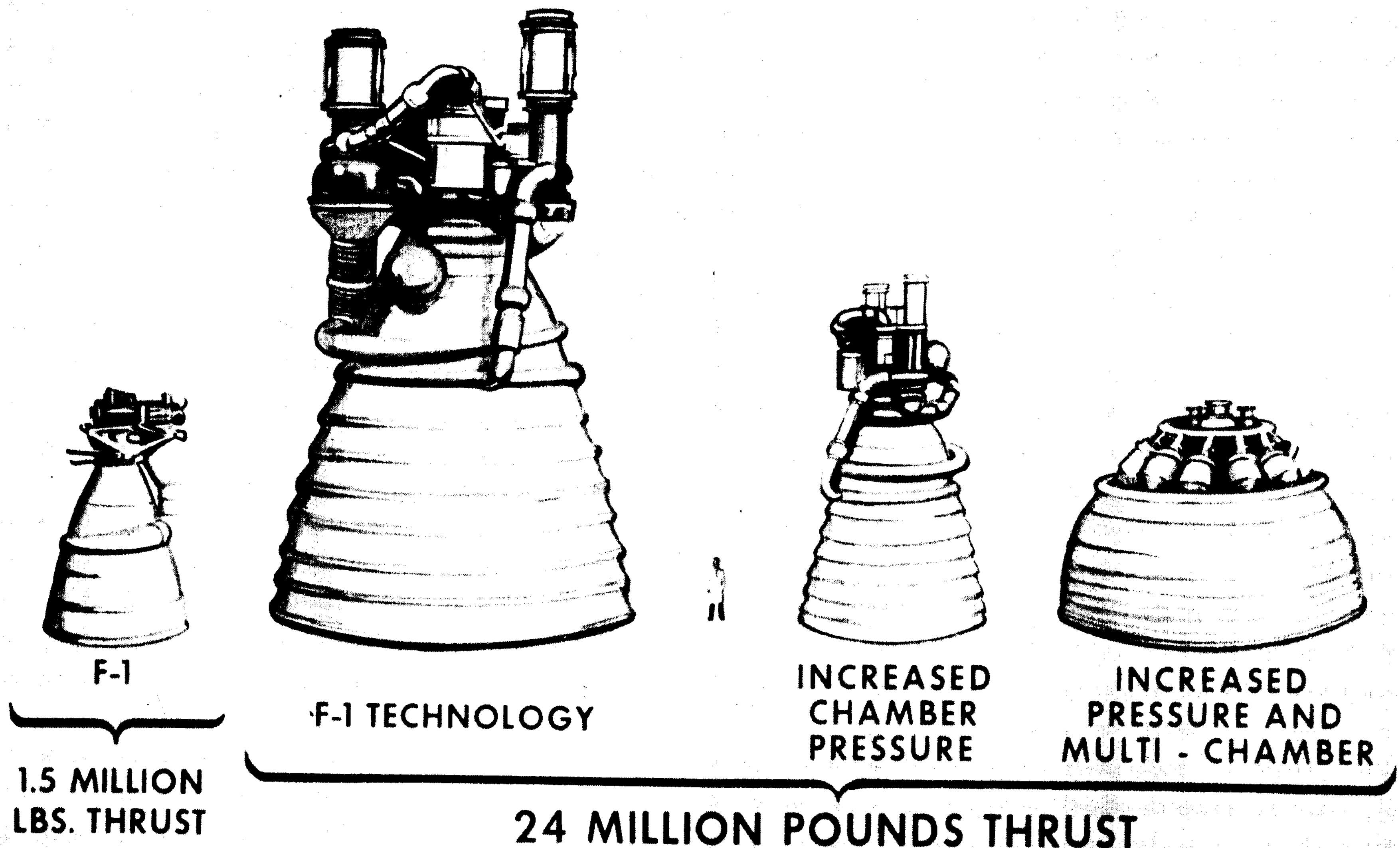
EXPLORER XVI ACCUMULATED PENETRATIONS



NASA RV64—359

Figure 2

SCALE-UP OF CONVENTIONAL AND ADVANCED CONCEPTS



NASA R63-333

Figure 3

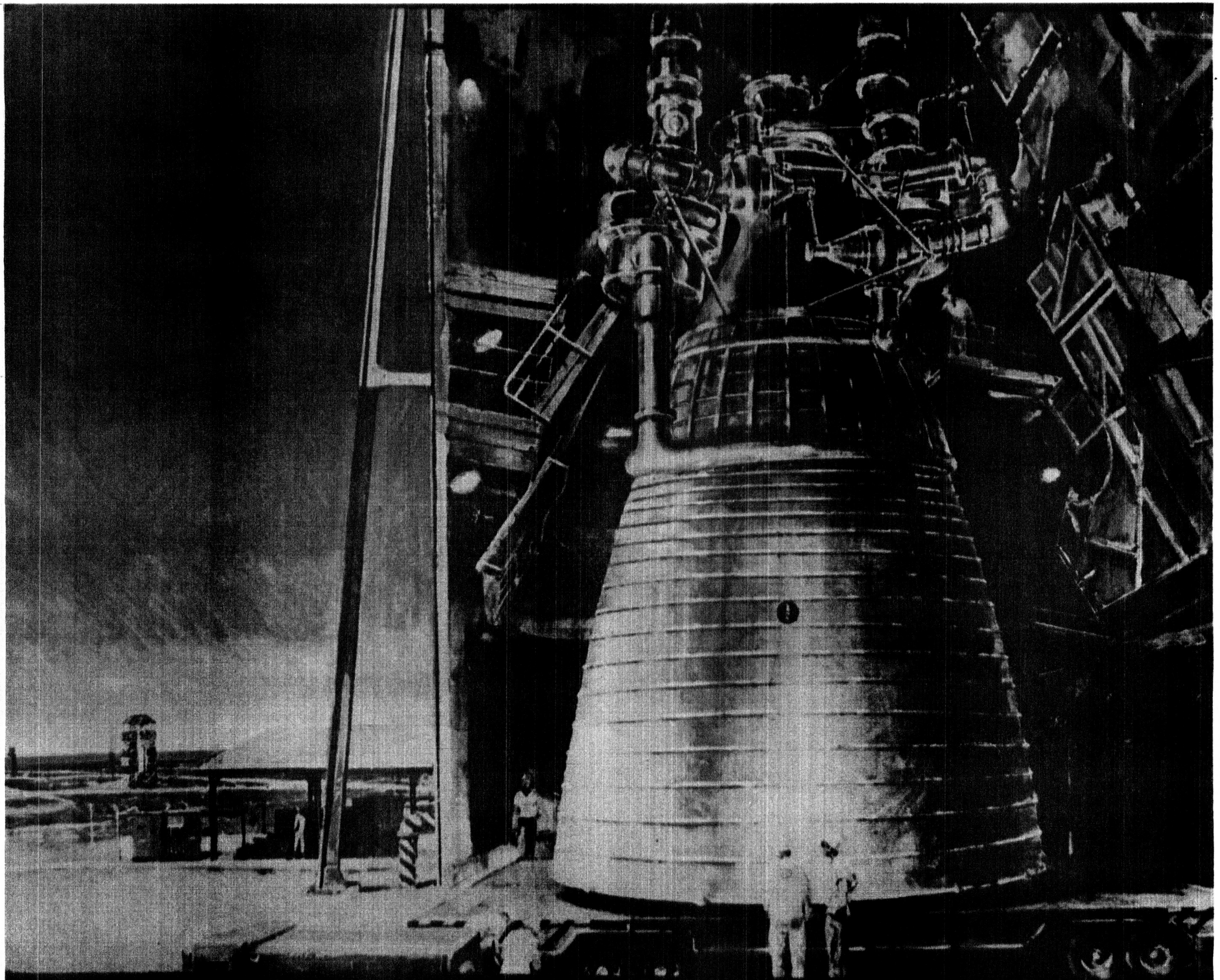


Figure 4

MAJOR NASA MILESTONES

PROGRAMS	LAUNCHES TO DATE	OBJECTIVES
MANNED		
MERCURY SERIES	6 (TWO SUBORBITAL)	MAN IN ORBIT
SCIENTIFIC		
PIONEER SERIES	7	LUNAR & INTERPLANETARY STUDIES
EXPLORER SERIES	13	NEAR SPACE STUDIES
VANGUARD SERIES	3	NEAR SPACE STUDIES
BEACON SERIES	2	NEAR SPACE STUDIES
OSO SERIES	1	SOLAR OBSERVATORY
RANGER SERIES	5	LUNAR PROBES & LANDING
MARINER SERIES	2	VENUS PROBES
APPLIED		
TIROS SERIES (METEOROLOGICAL)	7	WEATHER DATA
ECHO SERIES (COMMUNICATIONS)	4	BALLOON REFLECTOR
TELSTAR SERIES (COMMUNICATIONS)	2	INT'L TELECOMMUNICATIONS
RELAY SERIES (COMMUNICATIONS)	1	INT'L TELECOMMUNICATIONS
SYNCOM (COMMUNICATIONS)	1	FIXED POSITION SATELLITE FOR INT'L TELECOMMUNICATIONS
INTERNATIONAL		
ARIEL SCIENTIFIC	1	JOINT WITH GREAT BRITAIN
ALOUETTE SCIENTIFIC	1	JOINT WITH CANADA
LAUNCH VEHICLES		
SCOUT	3	SMALL PAYLOAD BOOSTER
CENTAUR	1	INTERMEDIATE PAYLOAD BOOSTER
SATURN	3	HEAVY PAYLOAD BOOSTER

Figure 5

A rapid increase in the number of activities will be expected in the coming years. Future planning foresees that in 1966 we will encounter a three-fold increase in the number of vehicles to be launched compared with 1963; vehicle size will increase sixfold; spacecraft size and weight will increase by a factor of 10; the amount of data required at each launch for comparison, will at least increase by a factor of 4. The compound effect of increased complexity of vehicles, the increase in launch rates, in addition to longer mission times will cause an increase in instrumentation requirements up to 20 times from today.

High reliability standards to accommodate for unattended operation over long periods of time are among the unique requirements for equipment in space. Mechanical, electrical, and optical parameters have to be measured to a degree of accuracy, surpassing in many instances the present state-of-the-art and leading to new approaches in measuring methods.

The measurement of mass, weight, and force, ties in with requirements which are unique, considering the range which these measurements must cover, and the specific environmental conditions under which they have to be performed.

In the field of rockets and space vehicles, weight and force measurements may be categorized as follows:

Calibration of tanks for filling, control and measurement of fuel consumption.

Calibration of flow meters.

Measure of the thrust of rockets and the calibration of load cells.

Determination of the take-off weight of a space vehicle.

Determination of the weight of individual stages and component parts.

Determination of the center of gravity.

Calibration of pressure gages.

Before the advent of space flight, variations of gravity at different locations were considered negligible. Therefore, weight, which is a function of gravity, and mass, which is an independent quantity, have been used interchangeably. The extreme accuracies required nowadays demand that attention be paid to their correct use. The weight of a body changes as the accelerating force of gravity varies, which on earth can differ up to a little more than 1/2% -- between a point close to the pole and one close to the equator. The mass of that body remains essentially the same, and in most engineering fields, these differences in gravity are negligible.

In the next Slide 6 we see how this difference in gravity is appreciable in space applications and can be used to stabilize a spacecraft. A dumbbell-shaped spacecraft in earth orbit will act like a pendulum and finally assume vertical attitude since the lower weight which is closer to earth weighs more than the higher weight.

Such values as fuel weight, lift-off weight will vary with the geographical location and, therefore, their actual masses must be determined for successful missions. Mass as a quantity of matter, or as a measure of the inertia of a body, derives its unit from the international standard in Paris. Our primary standard in the United States is at the National Bureau of Standards. Secondary standards or so-called dead weights have been calibrated by comparison with the primary standard. They are more appropriately called dead masses, because their weight will change with the location. As long as these systems are used at the same location, no corrections are required. However, at different locations--mass measurements on load cells, for example, must be corrected by a factor, the ratio of the gravitational accelerations of the two locations.

Another correction, which is required for the launching of space vehicles is the buoyancy effect. If the mass of a liquid fuel or any other liquid determined is determined by weighing, the buoyancy of the air taken into account. This buoyancy effect is about .015% and results in an error which varies with the material being weighed. For water it is about 0.11%; for liquid oxygen, 0.10%; for hydrocarbon fuels, 0.14%; for liquid hydrogen which has large variations in density, it can be between 1.5 and 4%. In this case the buoyancy must be calculated for each particular specific gravity. In determining the weight of complete launch vehicles similar corrections must be applied for the lift-off masses. The buoyant force adds to the thrust at lift-off, it diminishes with decreasing air densities during flight. For example, the fueled Jupiter missile has a specific gravity of .8, its buoyancy effect is 0.13%, its buoyant force, adding to the lift-off, is 158 lbs.

These considerations have to be taken into account when tanks are being calibrated for filling and for the measurement of the thrust of launch vehicles and the determination of the lift-off weight.

To convey an impression of size and other parameters of coming space vehicles:

In the next Slide 7, the Saturn launch vehicle family is shown with their respective payloads for a 100-mile orbit.

Saturn V will carry a payload of 90,000 lbs into an escape trajectory.

The S-I first stage develops a thrust of 1.5 million lbs.

The S-I-C develops 7.5 million lbs. of thrust.

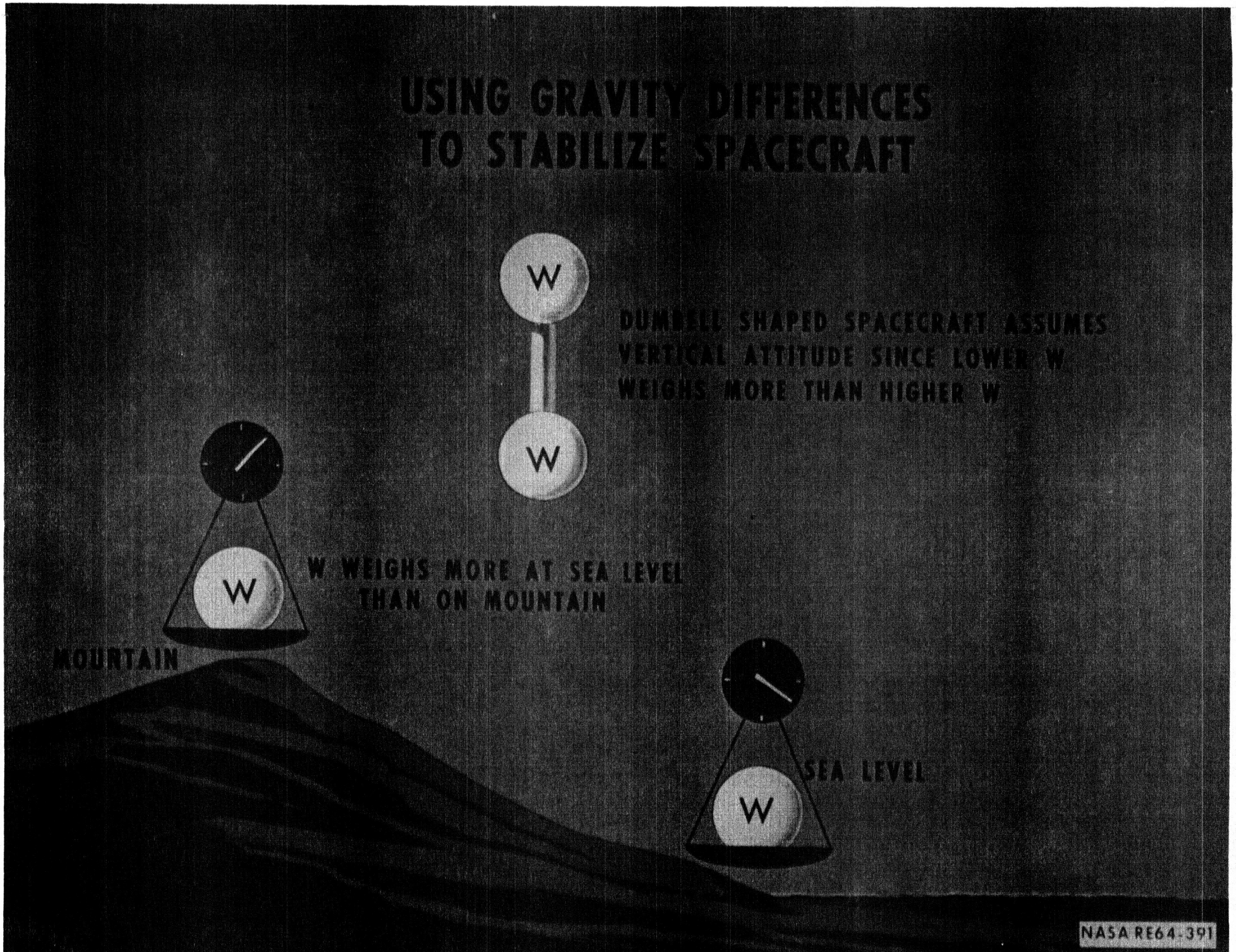

USING GRAVITY DIFFERENCES
TO STABILIZE SPACECRAFT
W
W
DUMBELL SHAPED SPACECRAFT ASSUMES
VERTICAL ATTITUDE SINCE LOWER W
WEIGHS MORE THAN HIGHER W
W
W WEIGHS MORE AT SEA LEVEL
THAN ON MOUNTAIN
MOUNTAIN
SEA LEVEL
W
NASA RE64-391

Figure 6

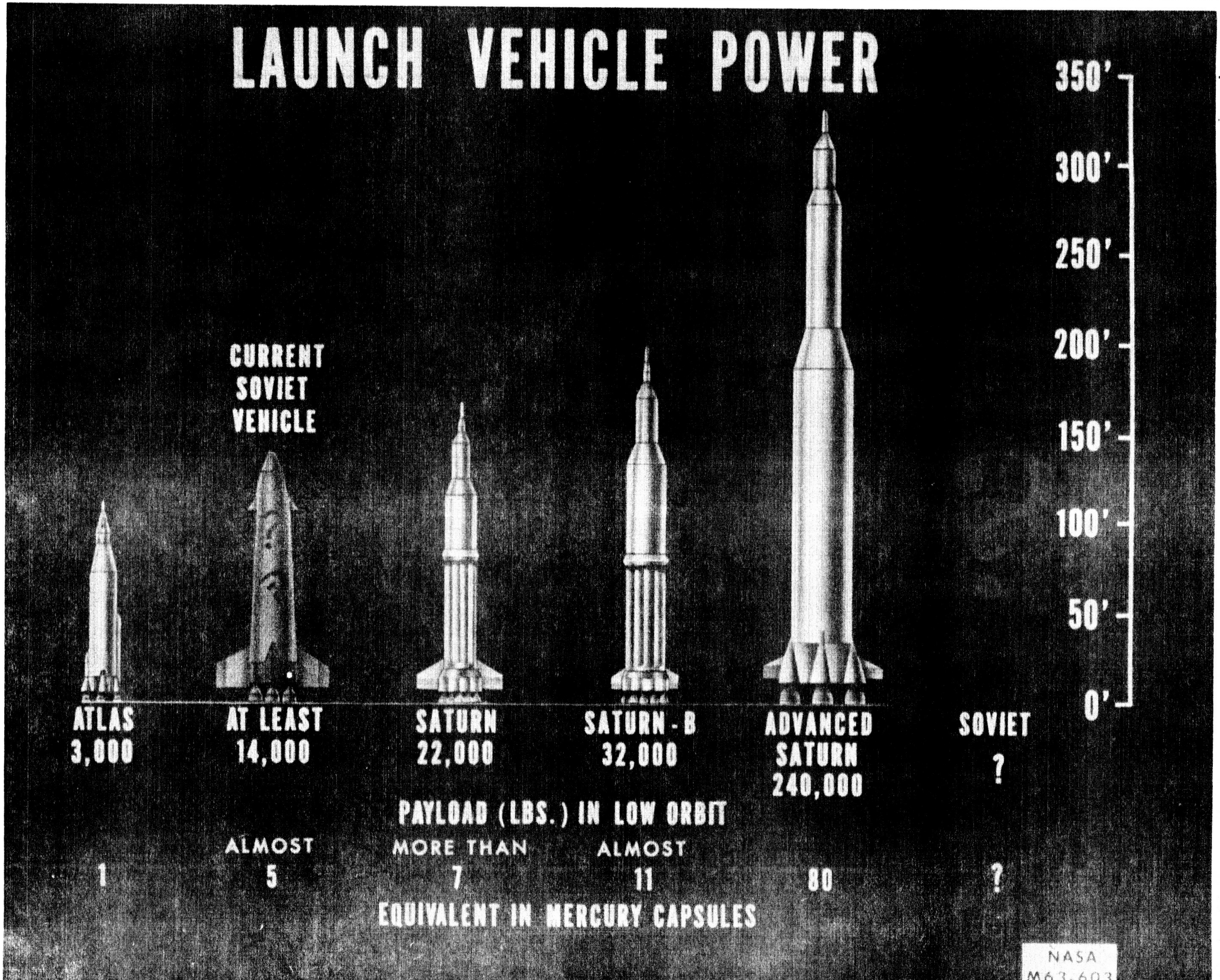

LAUNCH VEHICLE POWER
350'
300'
250'
200'
150'
100'
50'
0'
CURRENT SOVIET VEHICLE
ATLAS
3,000
AT LEAST
14,000
SATURN
22,000
SATURN - B
32,000
ADVANCED SATURN
240,000
SOVIET
?
PAYLOAD (LBS.) IN LOW ORBIT
1
ALMOST
5
MORE THAN
7
ALMOST
11
80
?
EQUIVALENT IN MERCURY CAPSULES
NASA
M63-603

Figure 7

The second stage S-IV develops 90,000 lbs., S-IV-B: 200,000 lbs., and S-II--one million lbs. of thrust.

The Saturn V is a three-stage device, the first stage of which will lift six million pounds from the earth's surface at Cape Kennedy to a speed of 6,000 miles per hour. Each of the five engines of the first stage has a thrust of 1,500,000 pounds and consumes three tons of fuel and oxygen per second. The second stage takes over and speeds the vehicle to 15,000 miles per hour. The third stage injects the remaining part of the Saturn V rocket and the Apollo spacecraft into earth orbit, and after it has coasted around the earth once, fires again to send off to the moon the forty-five ton Apollo spacecraft.

When we talk about the calibration of tanks we actually mean the determination of the capacity of the tank as a function of the liquid level. This calibration requires extreme accuracies which cannot be accomplished by placing the tank on a scale. Therefore, the common procedure has been to fill and drain the tank in incremental steps. The portions of the liquid drained in 20 to 50 steps into a barrel placed on a scale of relatively small capacity provides the means of determining the over-all fuel weight. The mass is then determined from the weight and density of the liquid. To apply correct density figures, parallel individual temperature measurements have to be made and compared with laboratory determined density versus temperature characteristics. Another correction, as previously mentioned, has to be made for the weight of the air in the barrel which is displaced by the liquid. This buoyancy correction also requires the measurement of the temperature and the pressure of the surrounding air which is displaced. Another problem occurs, when the tank which is being metered is intended for use of cryogenic propellants. Then a correction has to be made for the shrinkage of the tank. Very accurate weighings are needed to determine these shrinkage factors for different materials and temperatures.

Thus, we see that what used to be a single measurement of the capacity of a tank is getting quite involved.

In addition to density and temperature corrections, the level measurement requires correction in cases where the separation between liquid and gas is difficult to determine, as happens with liquid hydrogen.

However, there are other cases where the final measurement desired is a gravimetric quantity, best accomplished by direct weighing. Weighing systems have been devised for storage tank measurements to work with electric load cells. For low density liquids such as liquid hydrogen, the comparatively large tare or initial tank weight makes these measurements difficult. In the case of outdoor installations, the effects of wind velocity on large tanks must also be taken into account.

To meet some of our requirements, weighing systems have been built for measuring liquid hydrogen in tanks in which the gross weight of the fuel tank is 150,000 lbs. with a net capacity of 20,000 lbs. liquid hydrogen. In these systems load, cells metering the weight can be read out in increments of one pound from 0 to 20,000 lbs. Data can be taken every second. Thus, the difference of any two readings gives additionally the flow rate per second.

The next Slide 8 shows a load cell system under a launching platform designed for use with the Jupiter vehicle. Load cells are located in 3 legs 120° apart and alternately at 120° are hydraulic cylinders for unloading the cells for zero check. The system is shown being calibrated with dead weights.

The next Slide 9 shows 500,000 lbs. load cells for use with hydraulic cylinders in applying static loads to the Saturn test stand. The load cell with cover is completed. Mounted strain gages can be seen on the others.

Proper level gaging can be done by either continuous measurements or by level sensors located at fixed positions in the tank giving incremental measurements. A variety of these point sensors has been developed, making use of ultrasonic, optical, and capacitive type sensors.

In another system for weighing liquid hydrogen, the buoyant force on a weight or plummet in a liquid hydrogen tank is measured by a force transducer mounted above the tank. The plummet is connected to a balance beam and is balanced by a counter weight with no buoyant force on the plummet. Any unbalance sensed by load cells then measures the net buoyant force on the plummet. System accuracy is claimed to be .05% from 10 to 50 lbs. of buoyant force.

These accuracies are really required. In liquid propelled vehicles which make use of 2 propellants, correct amounts of the two propellants have to be loaded into the tanks, so that after being expended in the correct ratio neither one or the other remains in the tank after burnout. In launch vehicles such as Atlas or Titan, one pound of propellant is usually equivalent to a mile in range. To achieve orbital speeds and predetermined orbital parameters, highly accurate determination of the fuel consumption is even more critical.

I will now talk about flowmeters and their calibration. Calibration is accomplished by determining the quantity of liquid added or taken out of a tank during a certain time. This quantity can be determined by weighing. Formerly, this method was used exclusively, but now the use of level gages is often preferred to weighing.

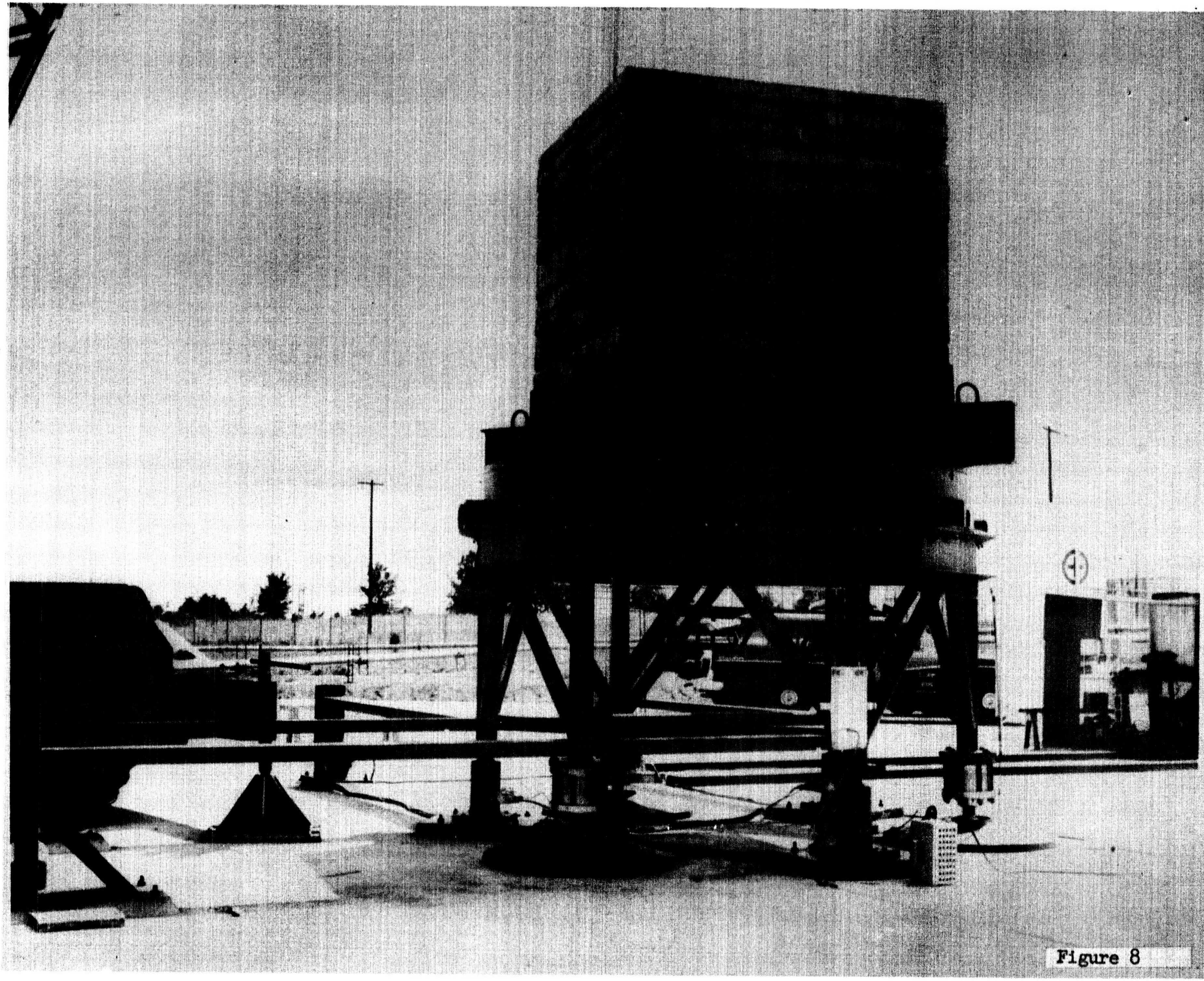


Figure 8

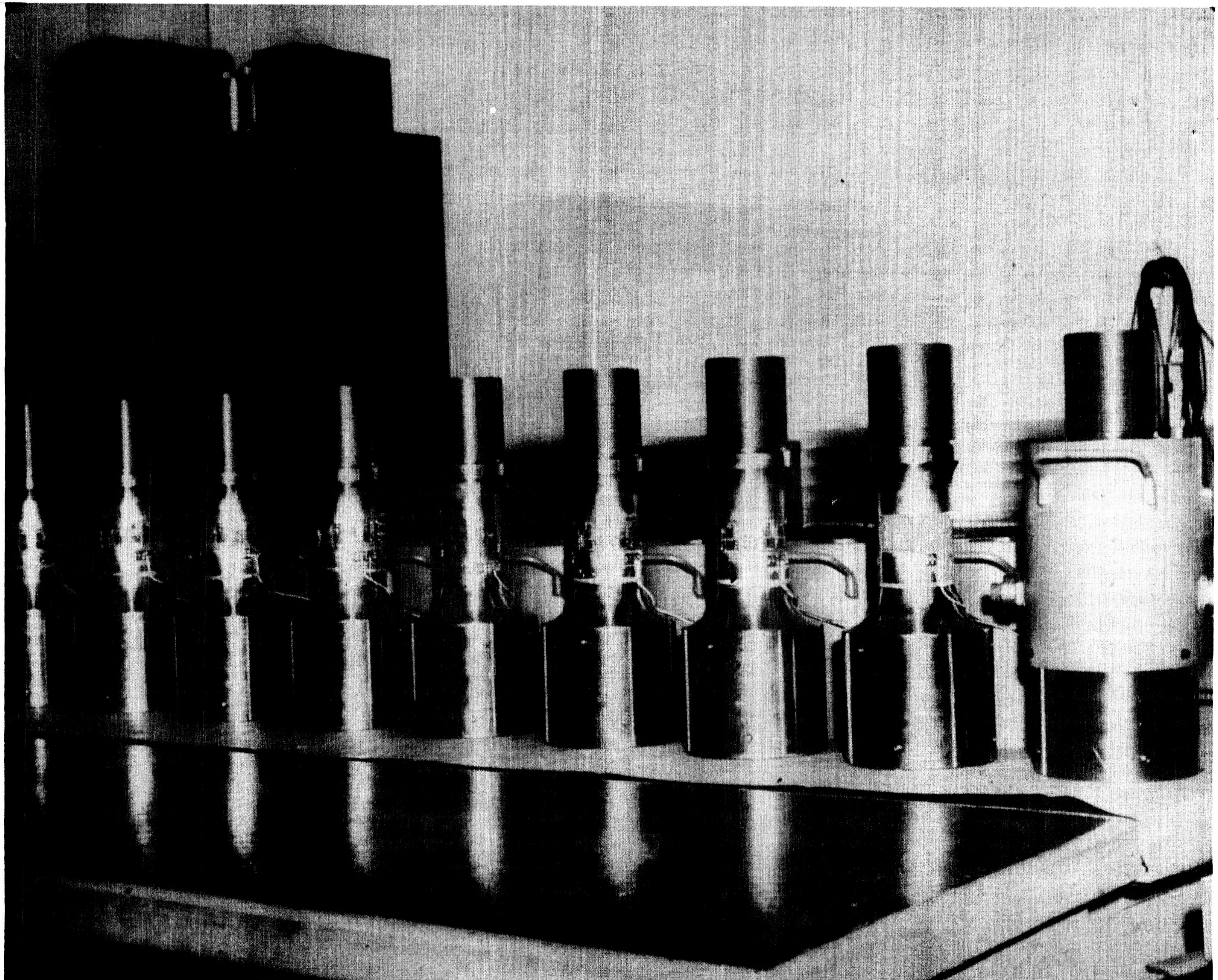


Figure 9

When calibrating flowmeters by weighing, it is important to take into consideration the absorption of weight in piping connections to the tank and to eliminate errors which might be introduced by drain lines. Another important point: consideration must be given to correct for the weight of gas in the liquid, when the liquid is forced out of the tank under pressure.

Liquid hydrogen is about 15 times lighter than water. Therefore, the weighing is especially critical when calibrating flowmeters for liquid hydrogen. Flowmeters have to be tested in the cryogenic media under actual flow conditions. Calibrations with water differ from calibration with liquid hydrogen by 3% and more. Recently, it has been found that a calibration performed with compressed air of 100 atmospheres will simulate the liquid hydrogen flow conditions to a high degree.

Since all flowmeter outputs become erratic at certain minimum flowrates, another problem is the difficulty of determining the zero of a flowmeter.

The next Slide 10: This system is used for the calibration of turbine-type flowmeters. Instrumentation and level gages can be seen. Note bellows attachment at bottom.

Recently, a liquid hydrogen flowmeter calibration facility has been built for NASA's Marshall Space Flight Center which has an accuracy of better than .15%. A mechanical scale is used in this system. Special care has been given to flexures and the arrangement of the drain line. The system works in the following way: The tare weights of the weighing system are so adjusted that the scale reaches zero balance soon after constant flow rate is accomplished. At this moment a zero switch starts a timer. Then, weights are dropped on the platform equivalent to the weight of the liquid hydrogen intended to be measured for calibration. At the moment this amount of hydrogen is consumed, the zero switch stops the timing system.

Determining the thrust of rockets is one of the most important measurements in space applications. Accuracy of the measurement depends on the accuracy of the load cells used to measure the thrust and, thus, on the accuracy of their calibration.

The need of thrust measurements has produced a large variety of force measuring systems since the start of rocket development. In early days, the thrust was usually measured with lever and knife edge scale systems which were an integral part of the test stand design. A capacitive load cell was used for dynamic measurements with an accuracy in the neighborhood of 5%. Later on, strain gage load cells gained in importance, and due to their steady improvement, are now becoming so accurate that they approach the accuracy of the national standards for weights. Bonded strain gage load cell measuring systems have been built with a verifiable accuracy of .05% of the applied load. Multiple cells are compared with the Bureau of Standards dead weight machine. In this way, the afore-mentioned accuracy can be attained up to one million pounds.

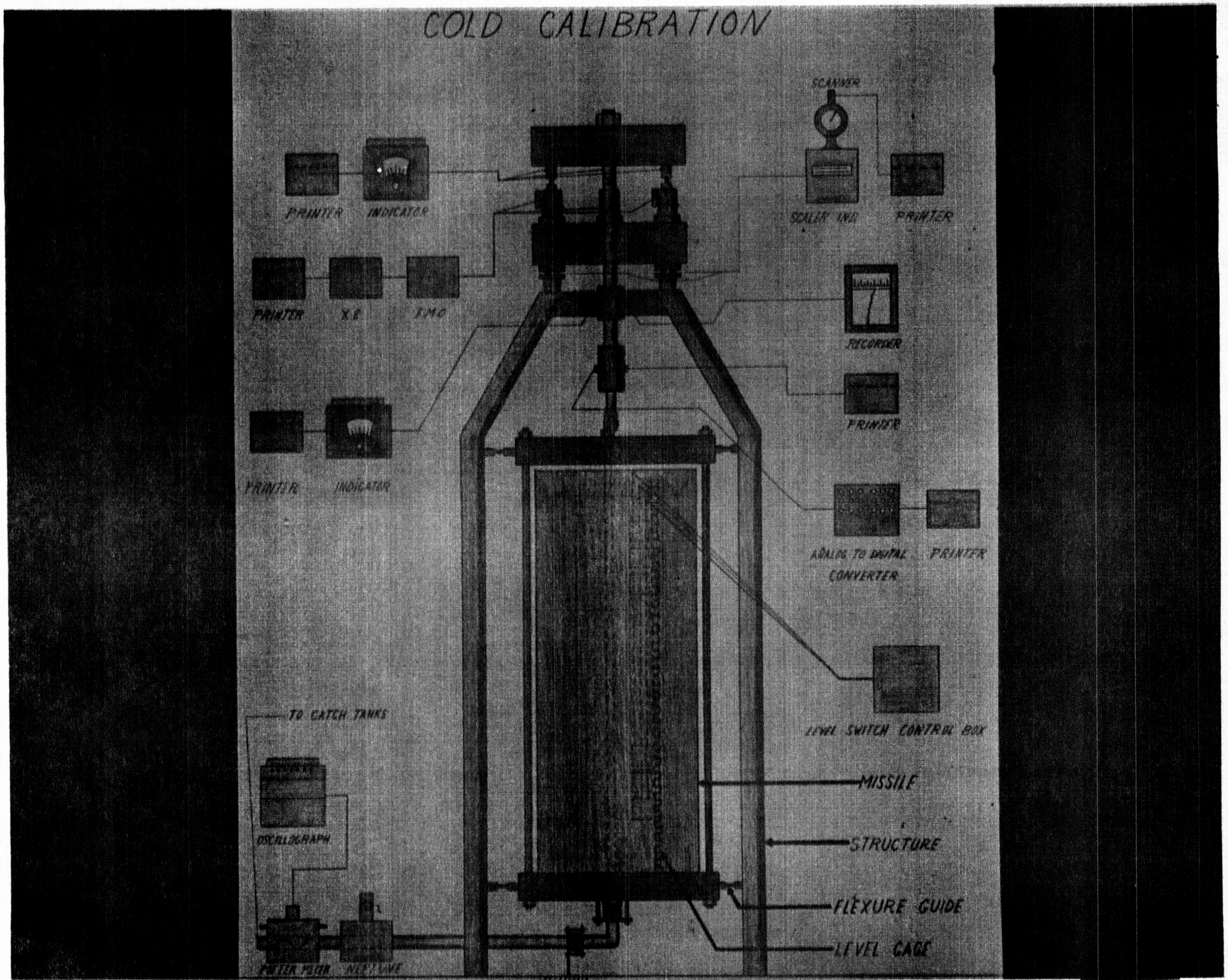

COLD CALIBRATION
SCANNER
PRINTER
INDICATOR
SCALER IND.
PRINTER
PRINTER
X.B
F.M.C
RECORDER
PRINTER
PRINTER
INDICATOR
ANALOG TO DIGITAL
CONVERTER
PRINTER
LEVEL SWITCH CONTROL BOX
TO CATCH TANKS
OSCILLOGRAPH
MISSILE
STRUCTURE
FLEXURE GUIDE
LEVEL CAGE

Figure 10

The Bureau just recently announced its capability of calibrating load cells for accurate measurements of weights up to 100,000 lbs. with an accuracy of five parts in a million.

Increasing the thrust past one million pounds has brought new problems to the load cell design. But it is an even bigger problem to design the test stand and the total thrust measuring system.

Next Slide 11: A three-cell system is shown for testing engines for specific performance. A second set of load cells serves for "in place" calibration of the thrust cells. Calibration cells are periodically checked in the laboratory for accuracy. In this case, thrust accuracy is reduced due to bellows and control connections from the stand to the engine.

A study is presently being conducted to determine the mass of individual stages with an interstage weighing system. Weighing of all the components and subsystems of a space vehicle is determined mostly by conventional means with mechanical scales. Weighing of all the component parts before assembly and the separate determination of the fuel in the tanks give together the take-off weight. The determination of the take-off weight is very important because this weight affects the trajectory calculations and flight analysis. Similarly, as for thrust measurements, load cells are used now for determining the take-off weight. Damage caused by the heat and flame of the rocket engine is another problem to be considered.

Next Slide 12: Here we have a view of the Saturn S-1C hold down arm with a 3.5 million-pound load cell. The vehicle outrigger is clamped in with a force of 2.1 million lbs., generated by an air motor through the gearbox actuator on the right side.

Next Slide 13: This is an artist conception of Saturn V held by one of the hold down arms.

In this connection it should be mentioned that the determination of the center of gravity or the center of mass of a space vehicle is likewise most important. It should be known as precisely as possible because trajectory calculations and the proper performance depend on the location of the center of gravity.

Finally, I will talk about the measurement of pressures. A multitude of pressure gages are being used in static and dynamic tests. The calibration of pressure gages has been performed with the conventional dead weight tester and the manometer. However, when a large number of pressure points are required for calibrating a wide range of transducers, manual calibration and manipulating of weights becomes a time consuming operation. Therefore, an automatic calibration method has been developed in which a sensitive equal arm balance is combined with a piston gage and an automatic weight handler drops weights on a pan of the balance according to a stored program on punched paper tape. The weights balance out the force of the piston acting on the other arm of the balance. Several systems have been built and are in use in various NASA Centers.

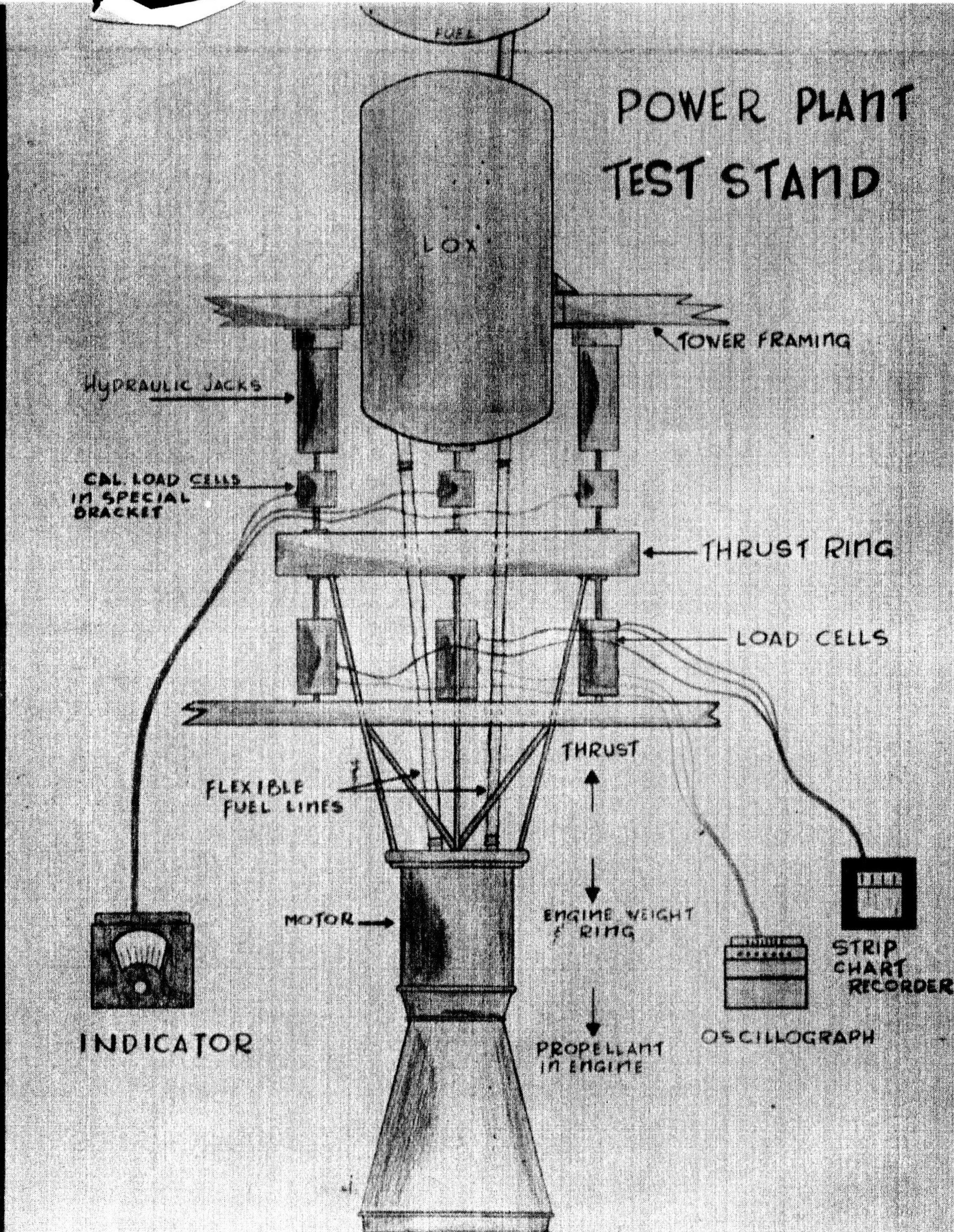
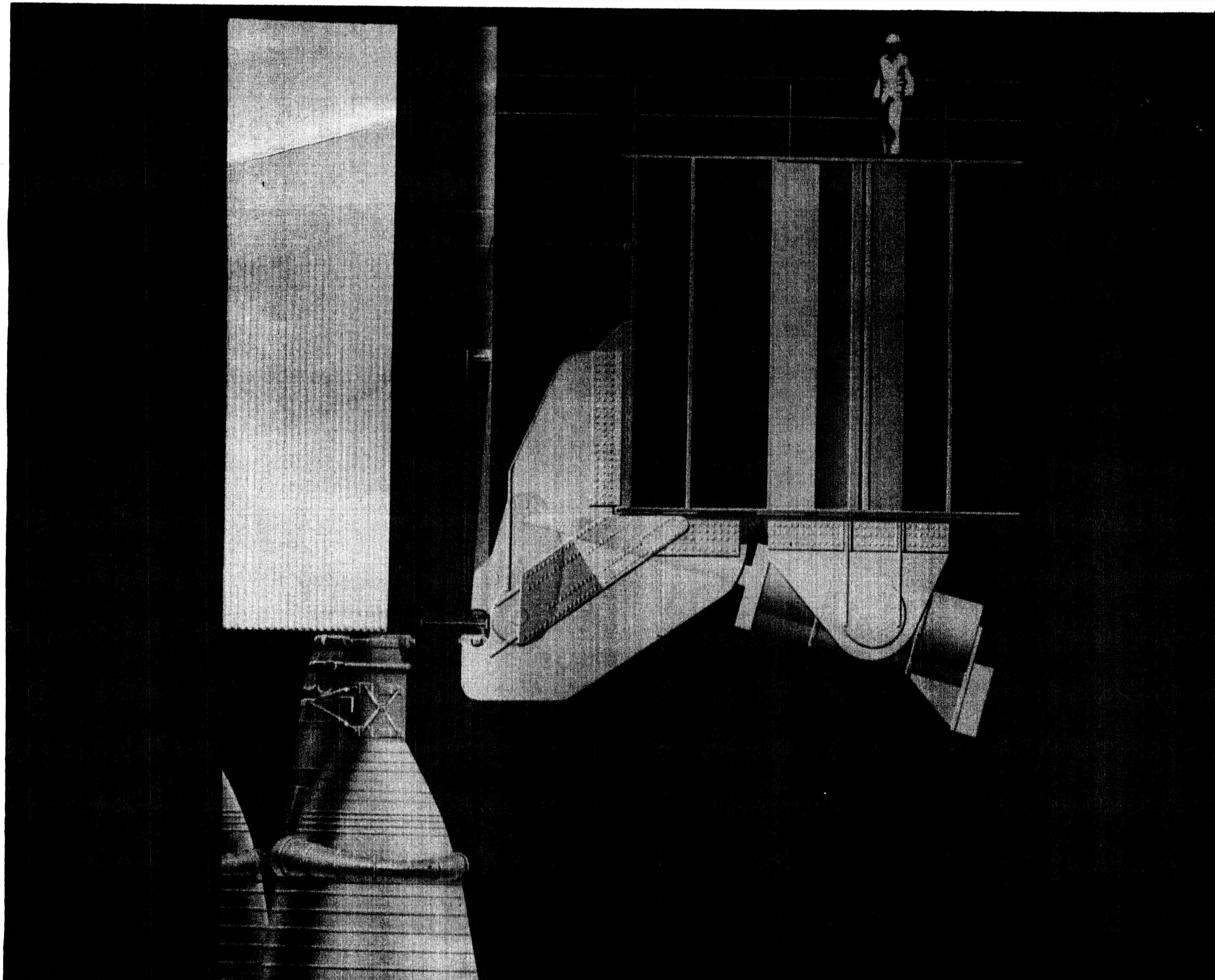

POWER PLANT
TEST STAND
FUEL
LOX
TOWER FRAMING
HYDRAULIC JACKS
CAL LOAD CELLS
IN SPECIAL
BRACKET
THRUST RING
LOAD CELLS
THRUST
FLEXIBLE
FUEL LINES
MOTOR
ENGINE WEIGHT
& RING
PROPELLANT
IN ENGINE
INDICATOR
OSCILLOGRAPH
STRIP
CHART
RECORDER

Figure 11



SATURN V STATIC HOLD DOWN ARM

Figure 12

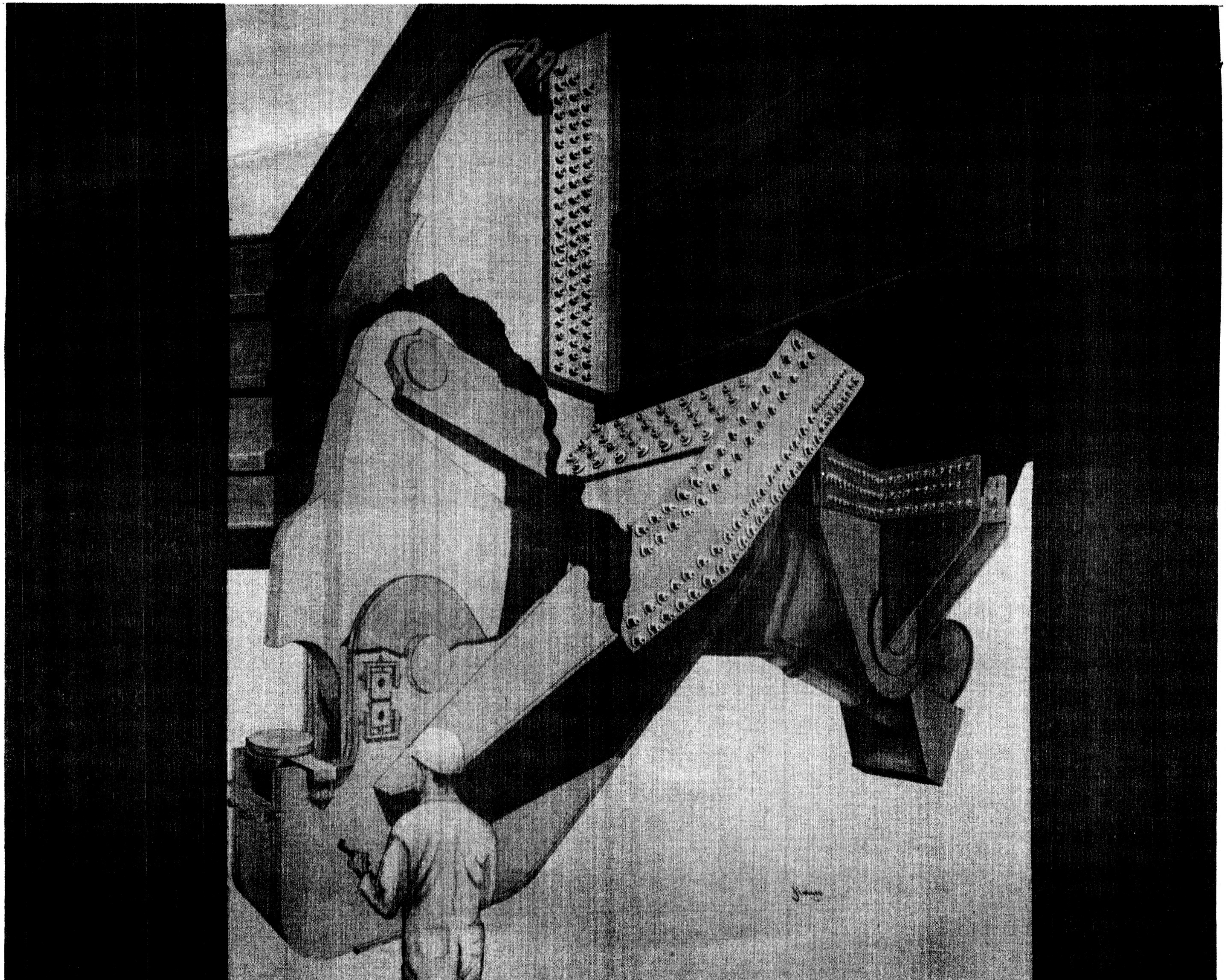


Figure 13

A calibration system for pressure transducers to be installed in the Saturn vehicle is being designed. It will have a range from .1 to 5,000 psi and can be set in steps of .1 psi up to one atmosphere and in steps of 1 psi from one atmosphere to full scale of 5,000 psi. Accuracies of .05% are expected and a reduction in measurement time is anticipated of 1/25 compared with manual operation.

In closing, it is my desire to point to the basis of all measuring problems and also to the problems connected with measurements, such as precision, accuracy, repeatability and reliability, by quoting Lord Kelvin. In very simple terms he said about one hundred years ago:

> I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it. But, when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the stage of science, whatever the matter may be.

I think we have followed this advice to arrive at our present capabilities.

As for the space program, what next? What is, in fact, done next must be determined by an assessment of the scientific, social, economic, and political implications. Exploration and extended visits on the lunar surface, large manned space stations, satellite television on a world-wide basis, world-wide weather coverage by satellites, the development of nuclear rockets.

No man can foresee the dividents which will accrue from the knowledge gained in this adventure. The President of the California Institute of Technology has said, "Already the dawning of the space age has impelled Americans to seek to improve their schools. That alone may be worth the cost of all of our space rockets."

- END -